Observational Evidence for Galaxy Evolution in the Local Group

Eline Tolstoy[1]

[1]UK Gemini Support Group, University of Oxford, Keble Rd, Oxford OX1 3RH, UK

Abstract

This review aims to give a summary of our understanding of galaxy evolution as infered from studies of nearby galaxies; how observations made with the *Hubble Space Telescope* have contributed significantly to our detailed understanding of the older stellar populations in Local Group dwarf galaxies. Recent results from VLT are also promising interesting future prospects for the study of resolved stellar populations in nearby dwarf galaxies.

1 Introduction

How do galaxies form and then evolve over time? This is one of the most fundamental questions in astronomy, and the answer has far reaching implications for the accurate interpretation of any observations of galaxies throughout the Universe. Galaxies are the end products of all the star formation in their entire lifetimes, and the ratios of chemical elements and remaining stellar population provide evidence for this past star formation. Only if we understand how galaxies change with time and especially how they may look when they are young can we use them to accurately understand what we see in galaxy surveys at high-redshift, because otherwise we don't know which type of galaxies we may be viewing. There are currently numerous techniques available to uncover information buried in the properties of individual stars. It will make a significant difference in the interpretation of galaxy surveys if they preferentially detect populations of star-bursting dwarf galaxies - which do not trace the mass distribution in the universe - or if the galaxies we detect are massive spirals or ellipticals which do. We thus have to understand how different types of galaxies evolve so we are able to distinguish their progenitors in redshift surveys.

It must be fair to assume that all the galaxies we see today in and around our Local Group are broadly representative; our region of space is neither over-dense (a cluster environoment) nor under-dense (in a void). All nearby galaxies have doubtless been forming and evolving for a significant fraction of the age of the Universe. If this were not true it would mean that our local region of space is in some way peculiar, and there is no evidence for this. Thus, as new techniques and instruments enable us to determine more and more accurate star formation histories for nearby galaxies over 90% of the lifetime of the Universe we can hope to obtain a representative picture of galaxy evolution from our local neighbourhood, and with it the ability to predict what galaxies look like at all redshifts. Detailed studies of nearby galaxies will thus provide an independent method to compare with redshift survey predictions.

It is apparent that some galaxies have a more or less constant global star formation rate through time (*e.g.* spirals) and some appear to be subject to sudden, intense *bursts* of star formation (*e.g.* irregulars) and then some stopped forming stars entirely at some point in the past (*e.g.* ellipticals). Filling in the crucial details of this basic scenario requires the detailed analysis of the fossil record of ancient star formation.

"Dwarf Galaxies and their Environment"; International Conference in Bad Honnef, Germany, 23-27 January 2001

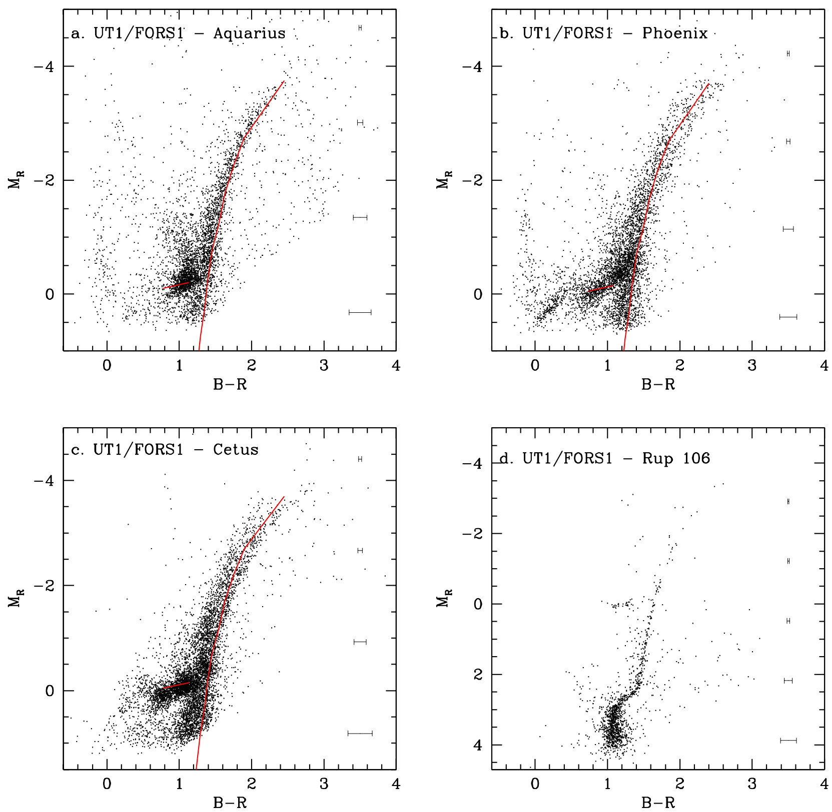

Figure 1: Here are plotted the Colour-Magnitude Diagrams for Local Group Dwarf galaxies (a) Aquarius, (b) Phoenix and (c) Cetus, and as a comparison, (d) the globular cluster Ruprecht 106, which resulted from UT1/FORS1 imaging in August 1999, in exceptional seeing conditions (Tolstoy *et al.* 2000). Representative error bars are also plotted for each data set. These data have not been corrected for any reddening effects. From the Ruprecht 106 data a fiducial mean was found for the RGB and HB. This is then over-plotted on each of the dwarf galaxy CMDs.

2 Imaging: Star-Formation Rate Evolution

The most detailed information on how a galaxy has evolved in time comes from measuring the star-formation rate as a function of time, or the star formation history (SFH), and the most direct and unambiguous method of doing this comes from interpreting CMDs of a significant fraction of the individual stars in a galaxy. This is a plot of the temperature versus the luminosity of all the stars bright enough to be detected in a galaxy in the observed quantities of colour and magnitude (see Figure 1). Because of our detailed understanding of stellar properties these measurements can be converted into physical parameters such as age (or SFH), chemical composition and enrichment history, initial mass function, environment, and dynamical history of a system. Some of these parameters are strongly correlated, such as chemical composition and age, since successive generations of stars may be progressively enriched in the heavier elements. Thus, detailed numerical simulations of CMD morphology are necessary to disentangle the complex effects of different stellar populations overlying each other and make an effective quantitative analysis of possible SFHs. To

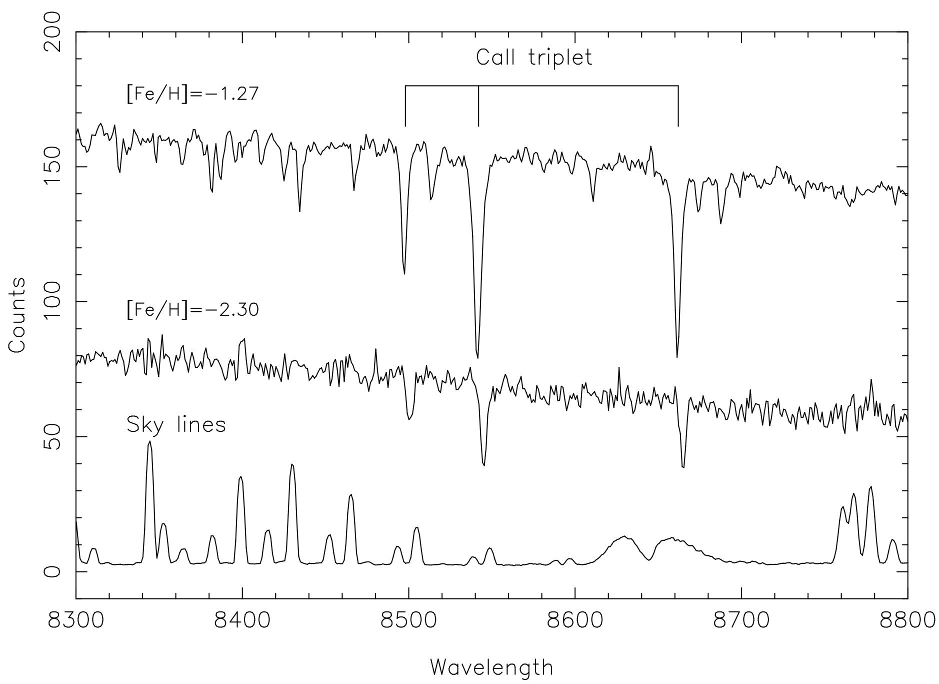

Figure 2: Here we show two examples of UT1/FORS1 low-resolution spectra of the Ca II triplet region of two red giant stars in the Sculptor and Fornax dwarf spheroidal galaxies observed in August 1999 (Tolstoy *et al.* 2001). They both lie at the opposite extremes of Ca II triplet line widths measured in our sample. For display purposes the spectra have been normalized to their continuum level and then arbitrarily shifted. The upper spectrum is of star c2-838 in Fornax with a calcium triplet metallicity of [Fe/H]= -1.27, and the lower spectrum is of star o1-1 in Sculptor, with [Fe/H]= -2.30. They both have good S/N, with $\sim$30 in the upper spectrum and $\sim$20 in the lower. Also shown here is the sky spectrum. This shows that, although this region of the spectrum is relatively free of bright sky lines, the weaker Ca II triplet line at 8498Å is more likely to be affected by sky lines than the other two.

this end There have been numerous recent developments in crowded field photometry techniques and advanced methods of interpreting highly populous and detailed CMDs from nearby galaxies (e.g., Tosi *et al.* 1991; Tolstoy & Saha 1996; Aparicio *et al.* 1996; Dolphin 1997; Dohm-Palmer *et al.* 1997; Hernandez *et al.* 1999; Harris & Zaritsky 2001).

The exquisite stable high spatial resolution combined with photometric accuracy of images from the *Hubble Space Telescope* (HST) have allowed us to probe further back into the history of star formation of a large variety of different galaxy types with widely differing star formation properties, and extend our studies out to the edges of the Local Group and beyond with greater accuracy than ever before. We have learnt several important things about dwarf galaxy evolution from these studies. Firstly we have found that no two galaxies have identical star formation histories; some galaxies may superficially look the same today, but they have invariably followed a different paths to this point. Now that we have managed to probe deep into the star formation history of dwarf irregular galaxies in the Local Group it is obvious that there are a number of similarities in their global properties with those of dwarf elliptical/spheroidal type galaxies, which

were previously thought to be quite distinct. However, the elliptical/speheroidals tend to have one or more discrete episodes of star formation through-out their history and dwarf irregulars are characterised by quasi-continuous star-formation. The previous strong dichotomy between these two classes has been weakened by these new results and may stem from the differences in the environment in which these similar mass galaxies were born into or have inhabited for most of their lives.

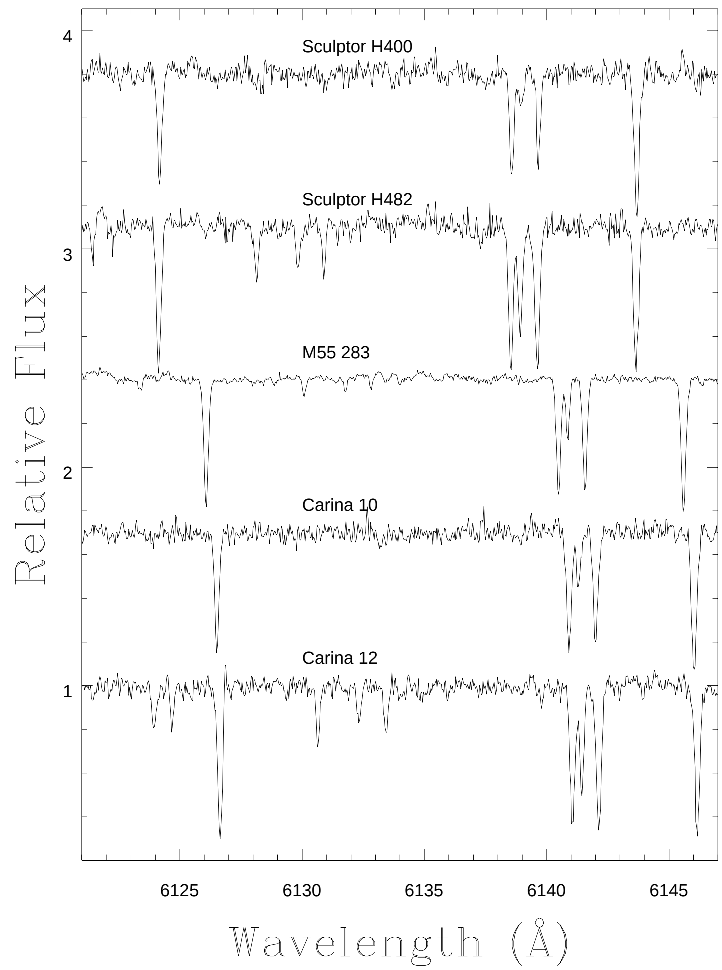

Figure 3: Here we show a small region of four UT2/UVES high-resolution spectra observed in August 2000 and January 2001 of stars in Sculptor and Carina dwarf spheroidals, and one of a comparison star in metal-poor globular cluster M 55 (Tolstoy, Venn, Shetrone, Hill, Primas, Kaufer & Szeifert in prep). Here we can see lines from Ca I ($\lambda\lambda$6122.2) Fe I ($\lambda\lambda$6136.6, 6137.7) and Ba II ($\lambda\lambda$6141.7). Clearly both Carina and Sculptor exhibit a range of abundance variation within their stellar population, and there are also interesting difference between the two galaxies.

3 Spectroscopy: Metallicity Evolution

If we want to understand the detailed chemical enrichment of galaxies by their constituent stars, we need to accurately measure the relative abundances of a range of different elements in high

resolution spectra. To date most metallicity determinations for stars in nearby galaxies (and there aren't many) have been derived either from single chemical element studies from low resolution spectra (see Figure 2) or from broad-band photometry, and these are at best simple estimates. Thus in spite of considerable efforts with 4m class telescopes, many of the most basic questions remain unanswered for most of the Local Group galaxies: What is the total range in [Fe/H] for stars within a galaxy? Does the [Fe/H] match that of the Milky Way halo populations (Globular clusters or field stars)? Do the elemental ratios (particularly [α/Fe] and [r- and s- process/Fe] ratios) in nearby systems track those seen in the metal poor field or in the globular clusters?

Results from high resolution spectra taken with HIRES at the Keck Observatory, have started to answer these detailed questions about the enrichment *history* of a variety of different elements within galaxies other than our own (e.g. Shetrone *et al.* 1998; Shetrone *et al.* 2001; Venn *et al.* 2001). The new ESO *Very Large Telescope* (VLT) observatory on Paranal in Chile consists of four 8m diameter mirror telescopes and a slew of modern instrumentation. The large collecting area and the high resolution spectrograph (UVES) allows us, amongst other things, to spectroscopically determine the abundances of a large variety of elements for individual stars (e.g., Hill *et al.* 2000; Primas *et al.* 2000). Recent results of UVES spectroscopy of stars of known age in a dwarf galaxy CMD are shown in Figure 3. By looking at galaxies outside our own we gain the advantages of perspective and thus we have a better chance to build up a complete picture of metallicity variations over time. The most interesting stars, to get a large range in age, are faint enough in external galaxies to require an 8m telescope. Including chemical evolution history in CMD analysis will result in a significant improvement in our understanding of how galaxies evolve.

For example, rather than just measuring a single present day end-product abundance of an element, we can select individual stars of different ages from imaging data and *measure* how the enrichment of many different elements has varied with time. This means we can measure how the chemical composition of the interstellar medium, the basic building material for future stellar populations, is altered by successive generations of stars. Deep, precision, multi-colour photometry in combination with spectroscopic metallicity measurements of the individual stars in external galaxies can uniquely determine the star formation histories of nearby galaxies going back many giga-years. These studies make clear the potential of deeper data, from VLT and new HST instruments, for a range of galaxy types.

4 Prospects for the future

We are currently (apparently) in the embarrassing situation of, at least claiming to, understand the properties of distant high-redshift galaxies better than those in the nearby Universe. It is only with the arrival of large telescopes with excellent image quality and high through-put spectrographs that we can start to make really detailed comparisons between the properties of distant and nearby galaxies. This is because the individual low mass (old) stars in the nearby universe which formed when the Universe was young (at high redshift) are faint. Thus to see them in galaxies external to our own requires at least an 8m class telescope.

There are a number of ways in which the current interpretation of CMDs can be dramatically improved. One is more and deeper CMDs of a larger sample of nearby galaxies. It is still most efficient to use HST to obtain deep CMDs to study the old main sequence turnoffs, but large scale surveys, down the magnitude of the Horizontal Branch can better be carried out with ground-based telescopes such as the VLT (see Figure 1). When galaxies are satellites of our own Milky Way, they are typically close enough that excellent results can best be achieved using wide field imagers on 2m class telescopes (e.g. MPA/ESO/2.2m WFI on La Silla or the INT/WFC on La Palma), of which there have been some nice results shown at this conference. I believe that the most important contributions will come from continuing the effort to improve our ability to interpret the details in

CMDs. There will be significant progress when we have measured abundances of a large variety of elements for stars of known age for individual stars in a CMD.

The observed redshift distribution of faint galaxies detected in deep UV/optical imaging surveys has been assumed to trace the star formation history of the Universe (e.g., Madau *et al.* 1996; Lilly *et al.* 1996). The majority of these galaxies are at intermediate redshift ($z < 1$), late type, intrinsically small, and undergoing a strong "burst" of star formation. This means that the nearby Universe (the Local Group) must contain clearly identifiable remnants from this relatively recent epoch $\sim 5 - 8$ Gyr before present (i.e. corresponding to $z \sim 0.5{-}1$) when the peak in the universal star formation rate is predicted to occur. Initial comparisons suggest that studies of nearby galaxies *do not* yield the same SFH as is inferred from optical redshift surveys (*e.g.*, Tolstoy 1998). However, the best present day candidates for this intermediate redshift galaxy population are the extremely numerous but presently faint (dwarf) irregular galaxies which have not yet been studied in sufficient detail. It is also true to say that although we know that nearby spirals and especially ellipticals have very large old stellar populations it is difficult to be very precise beyond about $8 - 10$ Gyr ago (corresponding to a redshift range z$> 1 - 2$) with current data. This is all going to change dramatically with large telescopes and more sensitive instruments. Sub-mm/radio wavelength surveys are also pointing to SFHs very different from those implied by optical data (e.g., Blain *et al.* 1999), and these surveys suggest a much larger type of galaxy (*e.g.*, ellipticals) which are typically at higher redshift ($z > 2$).

A complete survey of the resolved stellar populations in the local Universe will accurately trace star formation variations within both large and small galaxies, and determine if and when bursts of star formation occur and how long they last. It might well be that optical redshift surveys are strongly biased towards low mass dwarf irregular galaxies undergoing short bursts of star formation, and that they are thus not accurate indicators of the dominant mode (by mass) of star formation in the Universe which occurs in much larger galaxies.

The more detailed is our understanding of star formation processes and their effect on galaxy evolution in the nearby Universe the better we will understand the results from studies of the integrated light of galaxies in the high-redshift Universe.

References

Aparicio, A., Gallart, C., Chiosi, C. & Bertelli, G. 1996, ApJL, 469, 97
Blain, A. W., Smail, I., Ivison, R. J. & Kneib, J.-P. 1999, MNRAS, 302, 632
Dohm-Palmer, R. C., Skillman, E. D., Saha, A., Tolstoy, E., Gallagher, J. S., Hoessel, J. G., Mateo, M., & Chiosi, C. 1997, AJ, 114, 2527
Dolphin, A. 1997, New Astron. 2, 397
Harris, J. & Zaritsky, D. 2001, ApJS, in press
Hernandez, X., Valls-Gabaud, D. & Gilmore, G. 1999, MNRAS, 304, 705
Hill, V., François, P., Spite, M., Primas, F. & Spite, F. 2000, A&A, 364, 19L
Lilly, S. J., Le Fèvre, O., Hammer, F., & Crampton, D. 1996, ApJL, 460, 1
Madau, P., Ferguson, H. C., Dickinson, M., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388
Primas, F., Molaro, P., Bonifacio, P. & Hill, V. 2000, A&A, 362, 666
Shetrone, M. D., Bolte, M. & Stetson, P. B. 1998, AJ, 115, 1888
Shetrone, M. D., Côté, P. & Sargent, W. L. W. 2001, ApJ, 548, 592
Tolstoy, E. 1998, in "Dwarf Galaxies & Cosmology", eds T.X. Thuan *et al.*, p. 171
Tolstoy, E. & Saha, A. 1996, ApJ,
Tolstoy, E., Gallagher, J.S., Greggio, L., Tosi, M., De Marchi, G., Romaniello M., Minniti D. & Zijlstra A. 2000, "ESO Messenger", 99, 16
Tolstoy, E., Irwin, M. J., Cole A. A., Pasquini L., Gilmozzi R. & Gallagher J.S. 2001, submitted to MNRAS.
Tosi, M. M., Greggio, L., Marconi, G. & Focardi, P. 1991, AJ, 102, 951
Venn, K. A., Lennon, D. J., Kaufer, A., McCarthy, J. K., Przybilla, N., Kudritzki, R. P., Lemke, M., Skillman, E. D. & Smartt, S. J. 2001, ApJ, 547, 765